FRACTURE MECHANICS OF FIBROUS COMPOSITES

BY

WILLIAM JOHN SCHULZ

DEPARTMENT OF NAVAL ARCHITECTURE

AND MARINE ENGINEERING

MAY 1969

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WILLIAM JOHN SCHULZ

LIEUTENANT COMMANDER, UNITED STATES NAVY

B.S., UNITED STATES NAVAL ACADEMY
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ABSTRACT

The object of the work was to test the applicability of present testing procedures for fracture toughness testing of metallic materials when applied to fiber reinforced plastic. Samples were manufactured of polyester resin reinforced by a woven fiberglass cloth. A double edge notched specimen pulled in tension was used. Fracture toughness was computed using the procedure outlined in ASTM STP 410.

The effects of thickness, notch depth, and strain rate on fracture toughness was investigated. The results showed that the minimum specimen dimensions recommended for metallic materials could be further reduced for fiberglass composites.

Strain across the specimen was investigated as the point of application of applied force was varied. It was found that the strain was relatively constant acorss the specimen until the force was applied at points closer than twice the width of the specimen.

The last series of tests was made with the resin toughened by an elastomer. Improvement in fracture toughness resulted as small amounts of elastomer were added, but then decreased as the quantity of elastomer was further increased.

It is recommended that additional data be obtained to substantiate the trends displayed as a result of this series of tests and to test the effects of other specimen dimensions.

THESIS SUPERVISOR: F.J. MCGARRY

TITLE: PROFESSOR, DEPARTMENT OF CIVIL ENGINEERING

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a = crack depth - inches

a_o = initial notch depth - inches

b = half width of fracture toughness specimen - inches

B = specimen thickness - inches

E = elastic modulus - psi

F = force - pounds

K_I = opening mode stress intensity factor, KSI - $IN^{1/2}$

K_{IC} = plane strain crack toughness - KSI - $IN^{1/2}$

P = force - pounds

t = thickness - inches

w = specimen width - inches (tensile specimen)

W = specimen width - inches (Fracture toughness specimens)

Y = dimensionless coefficient (function of specimen dimensions)

ΔP = increment of force - pounds

ΔV = increment of strain - inches/inch

σ = normal stress applied at infinity - psi

σ_{ys} = yield strength - psi

I. INTRODUCTION

Composite materials have great potential for the engineer because their properties can be tailored to suit the situation, giving needed characteristics such as high strength/weight ratio, excellent resistance to corrosion and ease of maintenance. Fiberglass reinforced plastics, a combination of flexible glass strands and a plastic, usually of the thermosetting or heat hardening type, is one class of composite materials that is presently undergoing a rapid increase in commercial uses. Structures of new and unique designs are being proposed to be constructed of fiberglass reinforced plastics. Fiberglass boats one hundred feet in length are not uncommon, with proposals for increasing the size by a factor of three. However, before composites can be used to their maximum capabilities, there are many problems which must be solved. Among these problems are the prediction and evaluation of the mechanical properties of the composite. This report deals with the evaluation of the fracture toughness of a fibrous composite composed of a woven glass cloth in a matrix of polyester resin (Appendix A).

Fracture toughness is a measure of the resistance of materials to unstable crack extension. High resistance to unstable crack extension is desirable as materials that exhibit failure without warning, or which are extremely

sensitive to the presence of defects acting as stress concentrators, are limited in usefulness to stress levels significantly below their ultimate tensile stress.

Fracture toughness testing of fibrous composites is in its infancy. Although a great deal has been done with brittle metals, it is questionable if the practices and guidelines for metals can be used when testing composites. A comprehensive review of fracture toughness of metals has been compiled in two Special Technical Publications of the American Society for Testing and Materials (1,2). Several procedures discussed in these publications of the ASTM will be applied to a fibrous composite and the results compared to determine the feasibility of applying these standards of the ASTM for brittle metals to a fibrous composite.

II. PROCEDURE

Determination of a value of plane strain crack toughness, K_{IC} is accomplished in terms of the opening mode stress intensity factor K_I. The stress intensity factor was computed using two methods, both methods being based on the use of complex stress functions to solve crack extension problems. Bowie (4) developed polynomial mapping functions for use with the complex stress function technique. His results include a formula for the stress intensity factor.

$$K_1 = \sigma(\pi a)^{1/2} \left[\frac{2b}{\pi a}\left(\tan\frac{\pi a}{2b} + .1 \sin\frac{\pi a}{b}\right)\right]^{1/2}$$

This method was used for the initial calculations.

The American Society for Testing and Materials (2) applied Bowie's result to a curve fitting technique. The plot is a curve of 2a/W vs. Y. By entering with a value of 2a/W a value of Y is obtained which is a coefficient to be applied in the determination of K_I. The formula used is

$$K_1 = Y \frac{Pa}{BW}^{1/2}$$

By comparison with Bowie's formula it can be seen that Y is a function of the specimen geometry.

To determine a K_{IC} value, a crack notched specimen was increasingly loaded until the crack became unstable and extended abruptly. The value of K_I at which unstable crack extension is observed is the K_{IC} value determined from the test.

The material tested was fabricated using Laminac Polyester Resin 4173 (American Cyanamid Company) reinforced by style 181 fiberglass cloth (Stevens Fiberglass) and using methyl ethyl ketone peroxide as the catalyst to insure proper cure. See Appendix A for details of the fabrication. To investigate the possibility of improving the fracture toughness by the addition of elastomers to the matrix material a series of rubber modified laminates were manufactured. The technique was identical to Appendix A except for the included step of adding the elastomer and thoroughly mixing before adding the methyl ethyl ketone peroxide. The elastomer used was CTBN (B.F. Goodrich) and was added in amounts of 2.5, 5.0, 7.5 and 10.0 per cent by weight of resin. Heating the CTBN to 150°F before mixing aided the process by decreasing the viscosity of the CTBN and insuring thorough mixing.

The specimen size and geometry was that recommended by Brown and Srawley (3) and pictured in Figure 1. Tensile and fracture toughness specimens were cut and prepared from each laminate as detailed in Appendix B. All specimens were tested on an Instron Universal Testing Machine.

Tensile specimens were tested first to determine yield strength and elastic modulus. The Instron Universal Testing Machine was equipped with Type G-61 wedge action self aligning grips for the series of tests. The specimens

were pulled to destruction at a crosshead rate of .05 inches per minute. The elastic modulus was determined by clipping a Linear Variable Differential Transformer (PS - 3M WIEDEMAN LVDT) with a one inch gage length to each specimen. The LVDT gave a direct reading of stress vs. strain. The chart paper when driven by the LVDT would represent a displacement constant of .002 inches deflection/inch of specimen/inch recording paper. After the modulus was determined the specimen was taken to failure to determine yield strength.

The fracture toughness specimens were now tested. The specimens were machined so that tests could be run showing effect of thickness, notch depth, strain rate and rubber content on apparent K_{IC}. The specimens were axially loaded in tension and the load corresponding to unstable crack propagation and the particular crack length at this point of fracture instability was observed.

To insure that the fracture specimens were axially loaded a special end grip assemblage had to be constructed. The top grip was pinned to the load cell of the Instron while the bottom grip was pinned to the crosshead of the Instron. Both grips were identical as pictured in Figure 2. Securing the flat bearing plates as tightly as possible when testing the thicker specimens helped prevent failures from occurring at the end pins.

For determination of the material's fracture toughness characteristics, a knowledge of the particular crack

length corresponding to the load of fracture instability must be known. Various methods have been utilized for this purpose. A staining technique visually monitored during the test, was used for this series of tests. When the specimen was put under load, a drop of red India ink was introduced into the notch on each side of the specimen. As the crack propagated, the ink would be drawn through the specimen. It was hoped the ink would follow only during stable crack extension. However, it was observed that the ink would run after fracture tending to overestimate the true crack length. This was corrected by visually observing the specimen as the load was applied. The ink could be seen being drawn in during stable crack extension and the specimen could be continously marked with a pencil up to the point of unstable crack growth. When the specimen was removed from the Instron, the ink had run approximately 1/8 inch beyond the pencil mark, demonstrating that this procedure would cut down the error in crack length measurement.

Properties will vary with glass content of the specimen. An effort was made to maintain constant glass content as explained in Appendix A. To test glass content a sample was taken from each laminate, weighed, and put into an oven at $1000^{\circ}F$. The resin was burned off and the remaining cloth weighed and glass percentage determined.

A series of tests was also conducted to determine the strain across the specimen between the notches as the

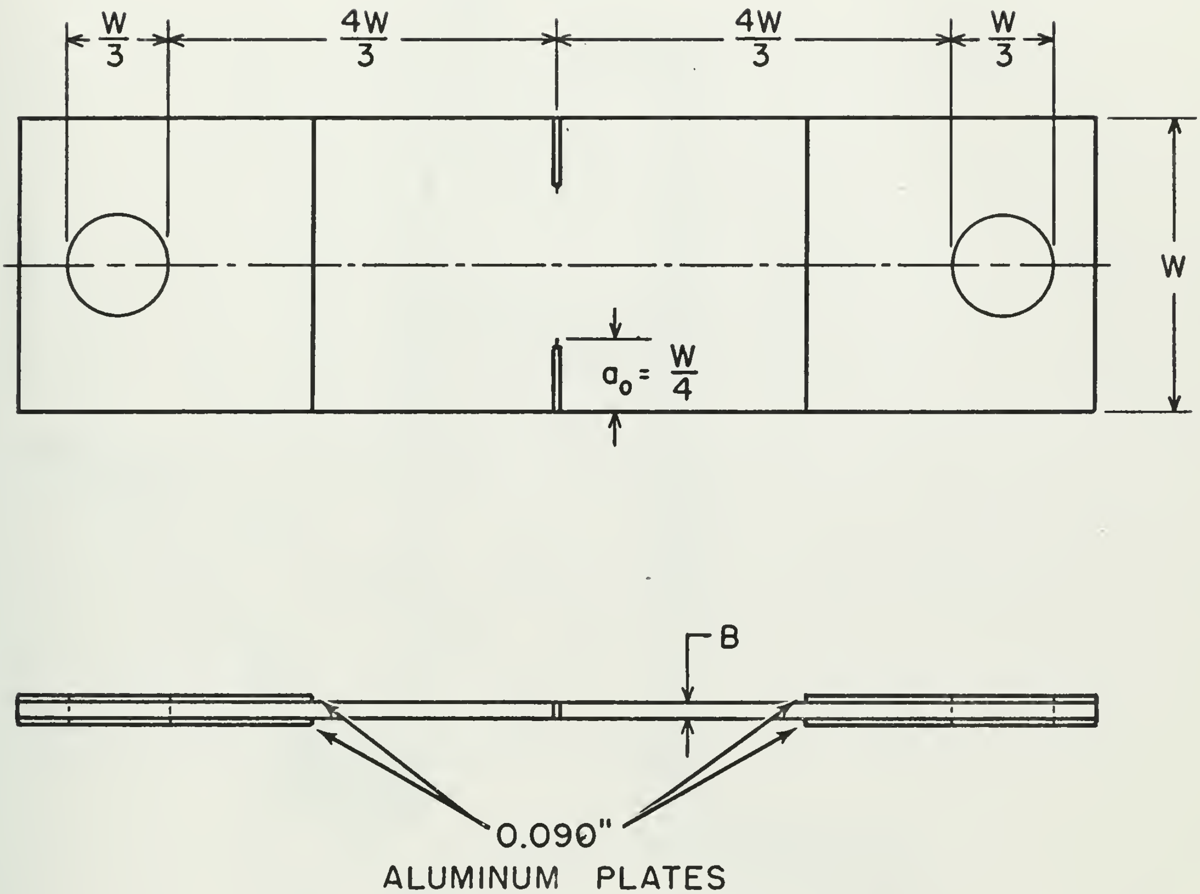


FIGURE 1. SPECIMEN GEOMETRY.

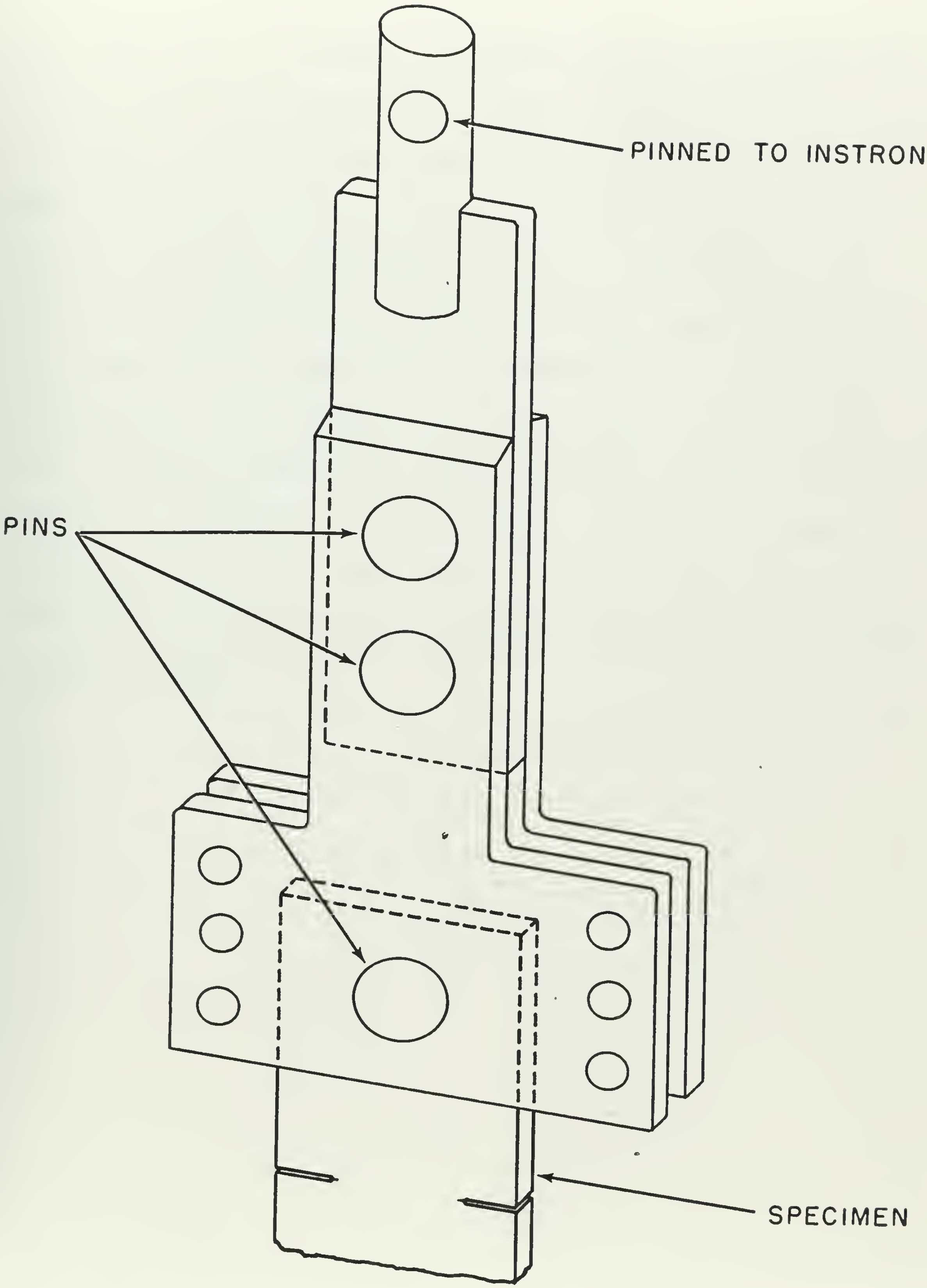


FIGURE 2. GRIP ASSEMBLAGE.

pin separation was varied. The center to center separation of the pins was varied between 4 and 10 inches and the strain monitored in the following way. Three SR-4 Strain Gages Type A-7, (BLH Electronics) were mounted on each specimen tested. They were positioned on a line joining the edge notches and numbered 1, 2, and 3. Strain Gage number 2 was positioned in the center of the specimen with 1 and 3 on either side midway between the center and the tip of the notch. The specimens were put in tension and the force increased in increments of 250 pounds. At each increment strain readings were taken from each gage using a BALDWIN SR4 STRAIN INDICATOR TYPE M giving a strain reading in micro-inches per inch.

III. RESULTS

The results of the experiments are displayed in the form of tables and graphs at the end of this section of the report. Data from which these results were obtained is presented in its entirety as Appendix C.

Results of the tensile tests performed showed that for the unmodified resin (no elastomer added) reinforced with 181 glass cloth there was no trend in either yield strength or elastic modulus with thickness. Average yield strength was 53,950 psi and elastic modulus of 2.643 x 10^6 psi. (See Table 1).

The next series of tests was to show the effect of thickness on apparent K_{IC} at a constant glass content. The laminates chosen for this ranged in glass content from 69.0 percent to 72.7 percent and ranged in thickness from 6 layers of cloth to 30 layers of cloth. The value of K_{IC} was found sensitive to thickness until a thickness of 15 to 18 layers was reached at which time the value of K_{IC} levelled out at approximately 17.5 KSI - $IN^{1/2}$. The value of $[K_{IC}/\sigma_{ys}]^2$ became constant at .119 inches at the same thickness. Both plots show a peak between 6 and 9 layers thickness. (See Figures 3 and 4.) A tabulation of results of computations of apparent K_{IC} using Bowie's formula and the curve fitting technique of the ASTM is shown in Table 2.

No effect of notch depth on apparent K_{IC} was shown to exist in the range of notch depth from 1/4 inch to 3/4 inch. (See Figure 5 and Table 3.)

Strain rate variations caused K_{IC} and $[K_{IC}/\sigma_{ys}]^2$ to pass through a minimum. Values decreased sharply with increasing strain rate until a strain rate of about .1 inch per min. At .5 inch per min. the values began to increase indicating a minimum between .1 and .5 inch per min. (See Figure 6 and Table 4.)

Investigating the strain field across the specimen between the notches showed a uniform field existed until the pin separation distance was reduced to four inches. At this point strains were greater at positions 1 and 3 and less at position 2 than with greater pin separation. (See Table 5.)

The last two series of tests were with a toughened matrix. The polyester resin was modified with an elastomer, CTBN, as explained previously in the procedure section.

Results of the tensile tests performed on laminates with a toughened matrix showed variations of both yield strength and elastic modulus with percentage of rubber added. Both went through a maximum at 2.5 percent and a nimimum at 7.5 percent. (See Table 6 and Figures 7 and 8.)

The effect of percentage of rubber on apparent K_{IC} showed a maximum at 2.5 percent. The value of K_{IC} was

increased from approximately 18.4 to 19.5 $KSI\text{-}IN^{1/2}$. A detrimental effect on K_{IC} is observed beyond 5 percent CTBN. The plot of $[K_{IC}/\sigma_{ys}]^2$ was reversed showing a minimum at about 3 percent rubber. (See Figure 9 and Table 7.)

TABLE 1

TENSILE TEST SUMMARY

Laminate	σ_{ys}	$E \times 10^{-6}$	Glass Content (%)
1-6	46.425	2.285	69.4
2-6	58,275	2.893	71.1
3-6	54,000	2.455	70.6
1-9	54,200	2.677	76.8
2-9	53,100	2.689	71.4
1-12	48,660	2.506	72.6
1-15	55,000	2.748	69.6
2-15	56,780	2.808	72.7
1-18	56,360	2.862	74.5
2-18	50,517	2.363	69.0
1-24	53,467	2.423	74.0
2-24	50,780	2.442	71.3
3-24	60,350	2.830	72.6
1-30	56,150	2.842	77.0
2-30	55,075	2.817	70.1

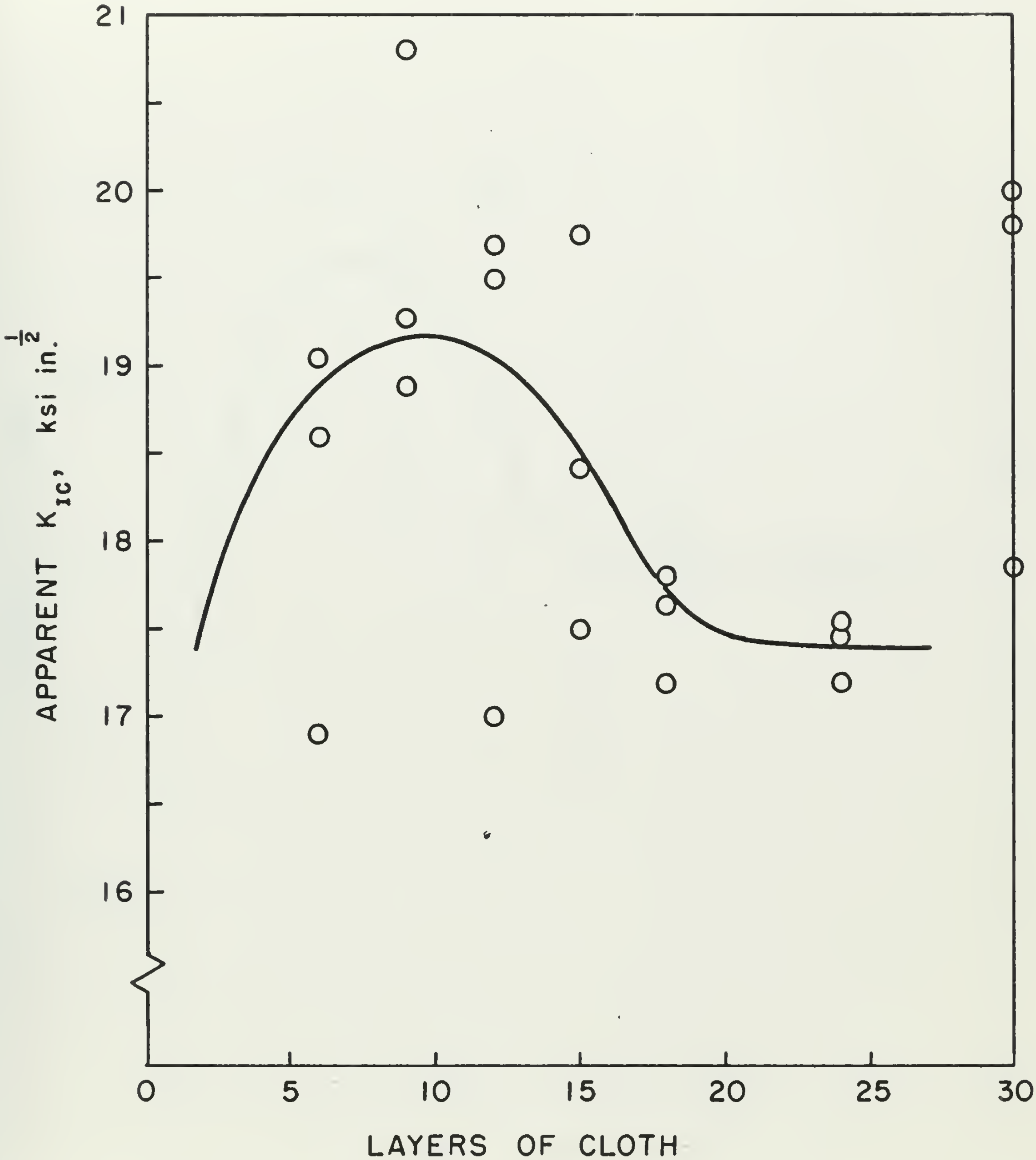


FIGURE 3. EFFECT OF THICKNESS ON APPARENT K_{IC} FOR 181 GLASS CLOTH LAMINATED WITH POLYESTER RESIN.

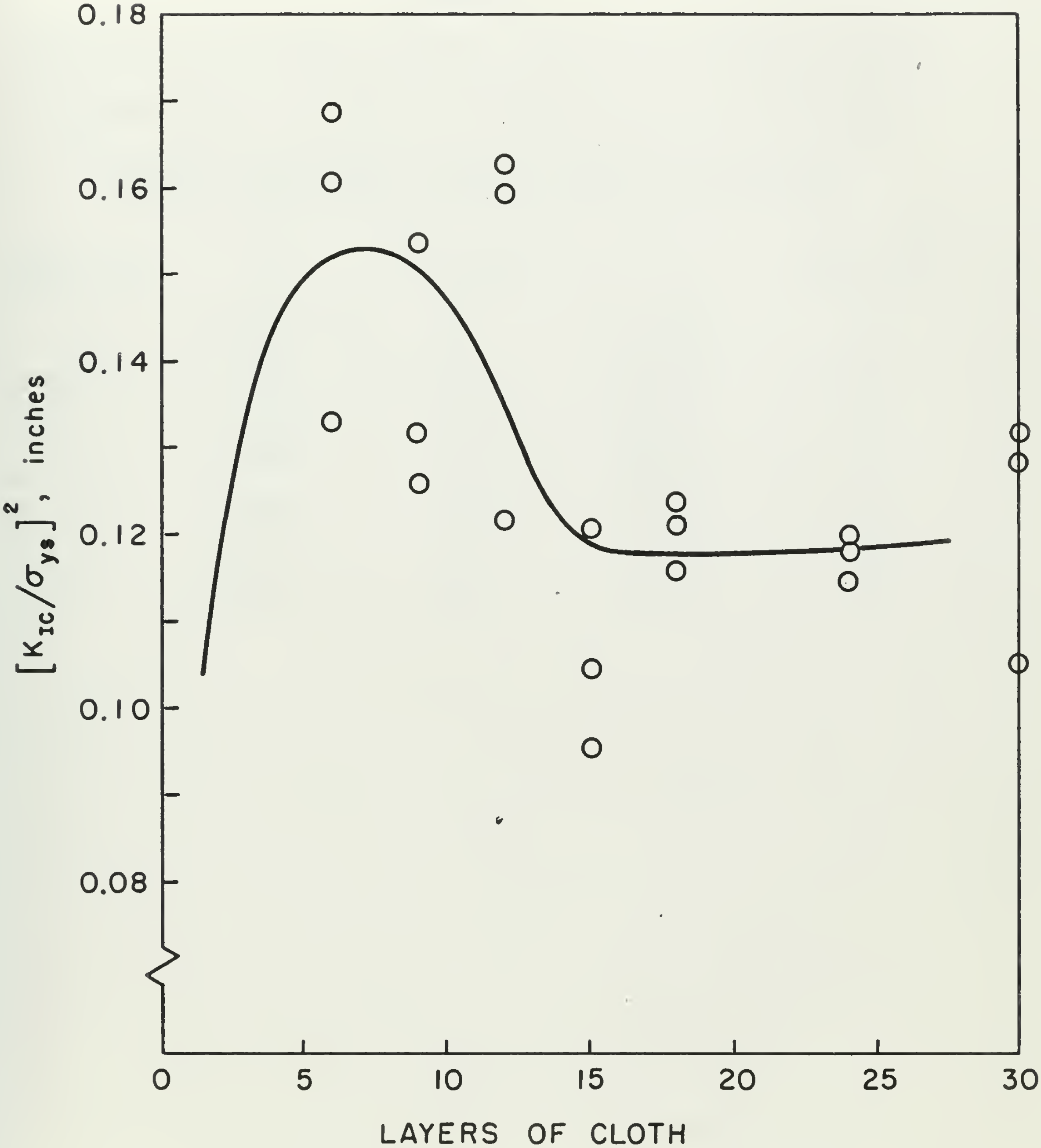
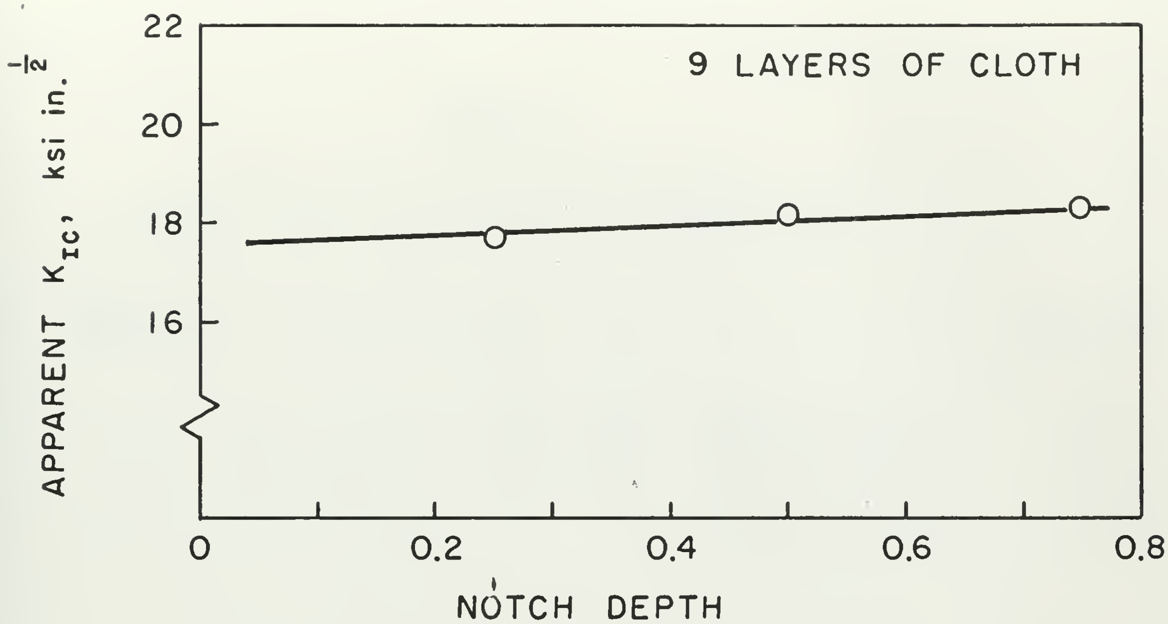


FIGURE 4. EFFECT OF THICKNESS ON $[K_{IC}/\sigma_{ys}]^2$ FOR 181 GLASS CLOTH LAMINATED WITH POLYESTER RESIN.

TABLE 2

COMPARISON OF BOWIE ANALYSIS AND K CALIBRATION CURVE OF BROWN AND SRAWLEY ON APPARENT K_{IC} VS. THICKNESS USING DOUBLE EDGE CRACKED PLATE IN TENSION

Laminate	K_1	$[K_1/\sigma_{ys}]^2$	K_1	$[K_1/\sigma_{ys}]^2$
2-30	19523	.126	19200	.122
2-24	17817	.123	17400	.118
2-18	17933	.126	17500	.121
2-15	19050	.113	18500	.107
1-12	19300	.158	18700	.148
2-9	20126	.144	19700	.137
1-6	18600	.161	18200	.154



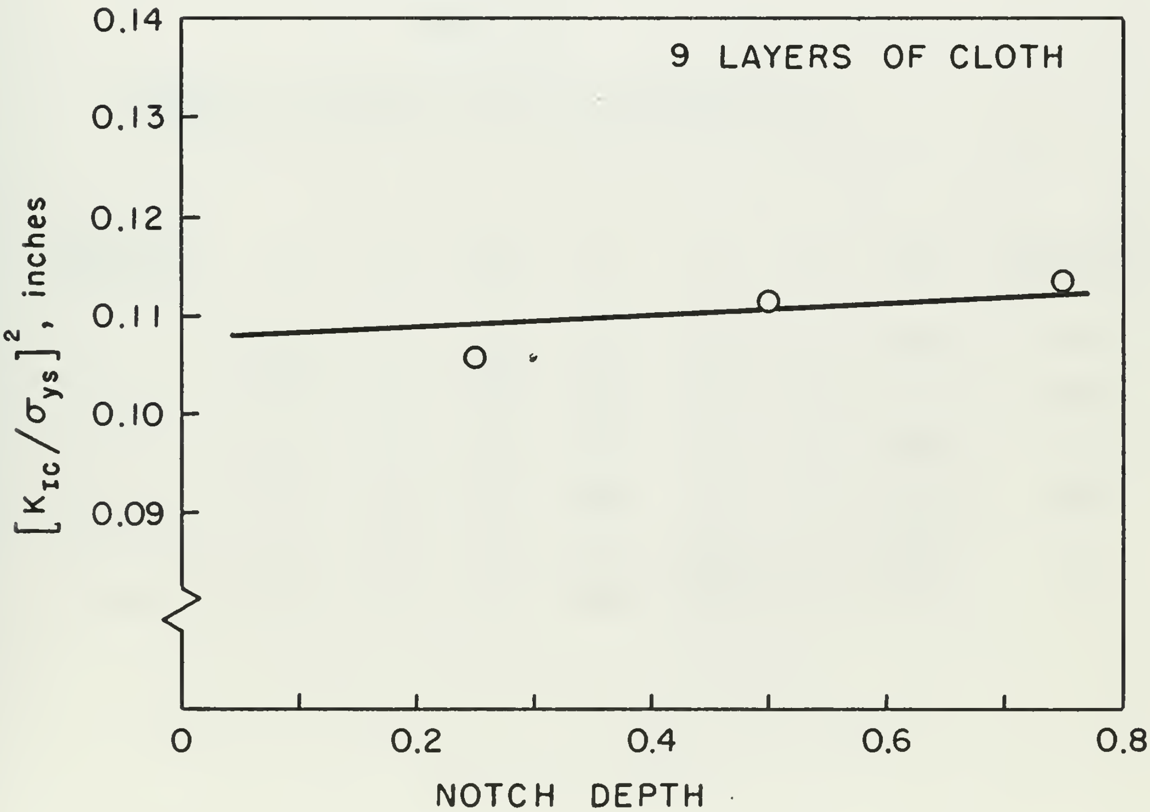


FIGURE 5. EFFECT OF NOTCH DEPTH ON APPARENT K_{IC} FOR 181 GLASS CLOTH LAMINATED WITH POLYESTER RESIN.

TABLE 3

EFFECT OF NOTCH DEPTH ON APPARENT K_{IC}

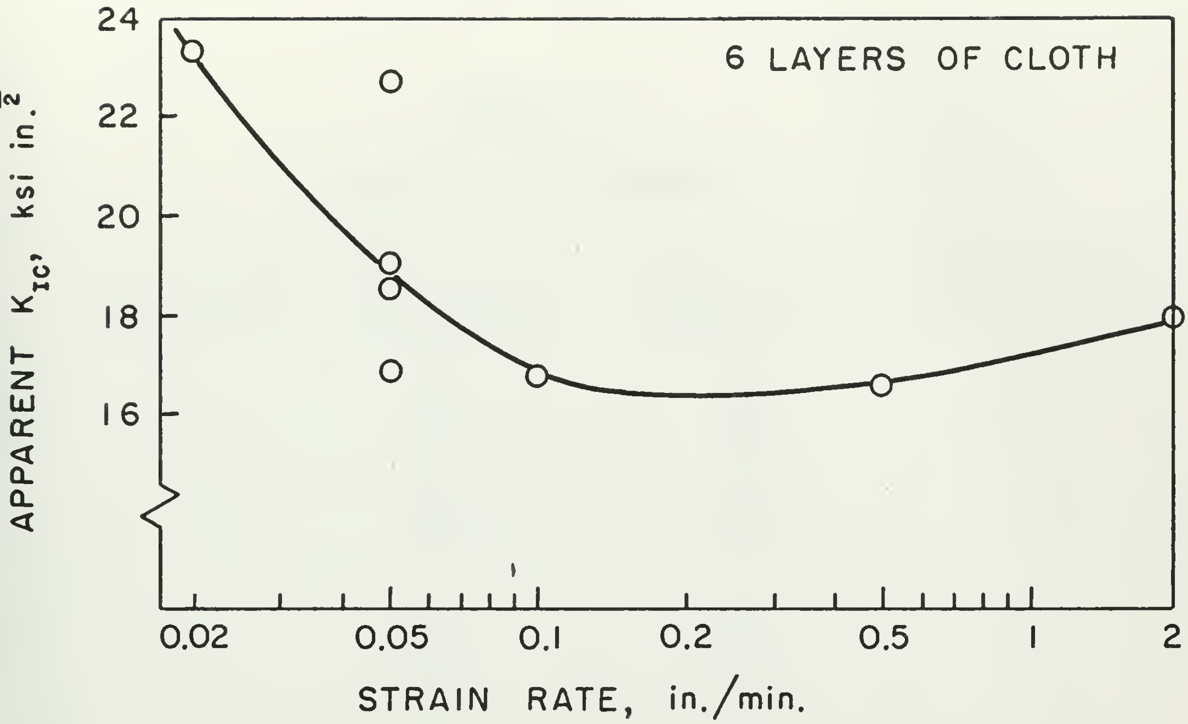
Notch Depth	Specimen Number	W	B	Web	P	a	Y	K_1	$[K_1/\sigma_{ys}]^2$
1/4"	1-9-1	3.004	.076	2.382	3550	.330	2.00	17650	.1059
1/2"	1-9-2	3.010	.072	1.878	2600	.581	2.01	18200	.1115
3/4"	1-9-3	3.015	.077	1.512	2375	.757	2.06	18300	.1139

TABLE 4

EFFECT OF STRAIN RATE ON APPARENT K_{IC}

Cross-head Rate*	Specimen Number	W	B	Web	P	a	Y	K_1	$[K_1/\sigma_{ys}]^2$
.01	2-6-1	3.036	.044	.566	1120	1.240	2.63	24500	.178
.02	2-6-2	3.040	.044	.120	920	1.460	2.80	23400	.161
.05	2-6-3	2.920	.045	1.292	1560	.814	2.12	22800	.153
.1	3-6-1	2.970	.053	1.367	1405	.802	2.09	16700	.096
.5	3-6-2	3.031	.052	1.377	1370	.827	2.10	16500	.094
2.0	3-6-3	3.036	.050	1.432	1440	.802	2.09	17800	.109

* (in/min)



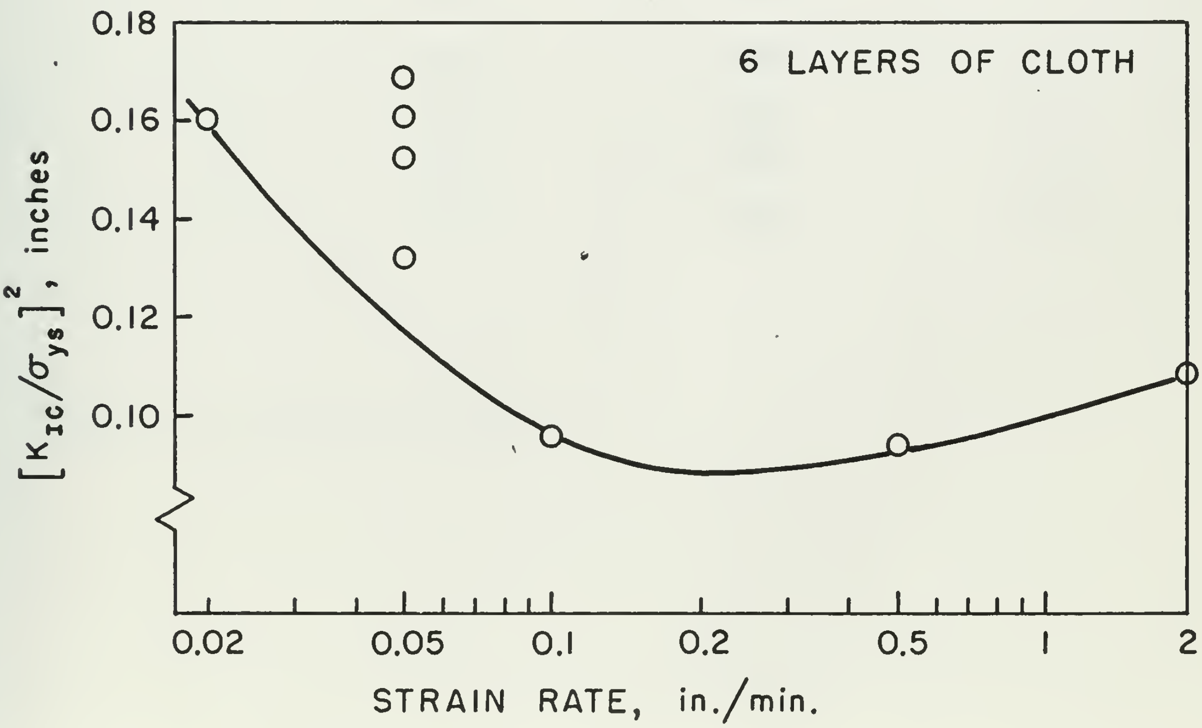


FIGURE 6. EFFECT OF STRAIN RATE ON APPARENT K_{IC} FOR 181 GLASS CLOTH LAMINATED WITH POLYESTER RESIN.

TABLE 5

STRAIN FIELD SUMMARY

	Pin Center Separation	Total Strain Position 1	Total Strain Position 2	Total Strain Position 3
Force 1000 lb.	10	566	570	630
	8	585	560	575
	6	595	540	535
	4	768	428	585
Force 2000 lb.	10	1116	1120	1220
	8	1160	1100	1140
	6	1165	1040	1025
	4	1598	888	1240
Force 3000 lb.	10	1666	1605	1700
	8	1730	1610	1630
	6	1765	1580	1555
	4	2573	1403	1980

Strain in microinches/inch.

TABLE 6

TENSILE TESTS SUMMARY

(Rubber Modified Specimens)

% Rubber Specimen Number	w	t	F	σ_{ys}	ΔP	ΔV	$E \times 10^{-6}$
2.5-1	.481	.115	3350	60600	1000	.006	3.01
2.5-2	.474	.112	3350	63000	1000	.006	3.13
2.5-3	.466	.109	3150	62000	975	.006	3.20
2.5-4	.476	.106	3400	67400	950	.006	3.14
5.0-1	.488	.127	3325	53600	1050	.006	2.82
5.0-2	.485	.129	3500	56000	950	.006	2.53
5.0-3	.475	.132	3400	54300	950	.006	2.53
5.0-4	.479	.136	3450	53000	950	.006	2.43
7.5-1	.490	.154	3600	47800	1000	.006	2.21
7.5-2	.486	.154	3450	46200	975	.006	2.17
7.5-3	.496	.155	3400	44200	1025	.006	2.22
7.5-4	.499	.155	3715	47900	1000	.006	2.16
10.0-1	.490	.126	3300	53400	1000	.006	2.70
10.0-2	.492	.123	3300	54600	950	.006	2.62
10.0-3	.492	.129	3350	53000	950	.006	2.50
10.0-4	.495	.134	3325	50000	950	.006	2.38

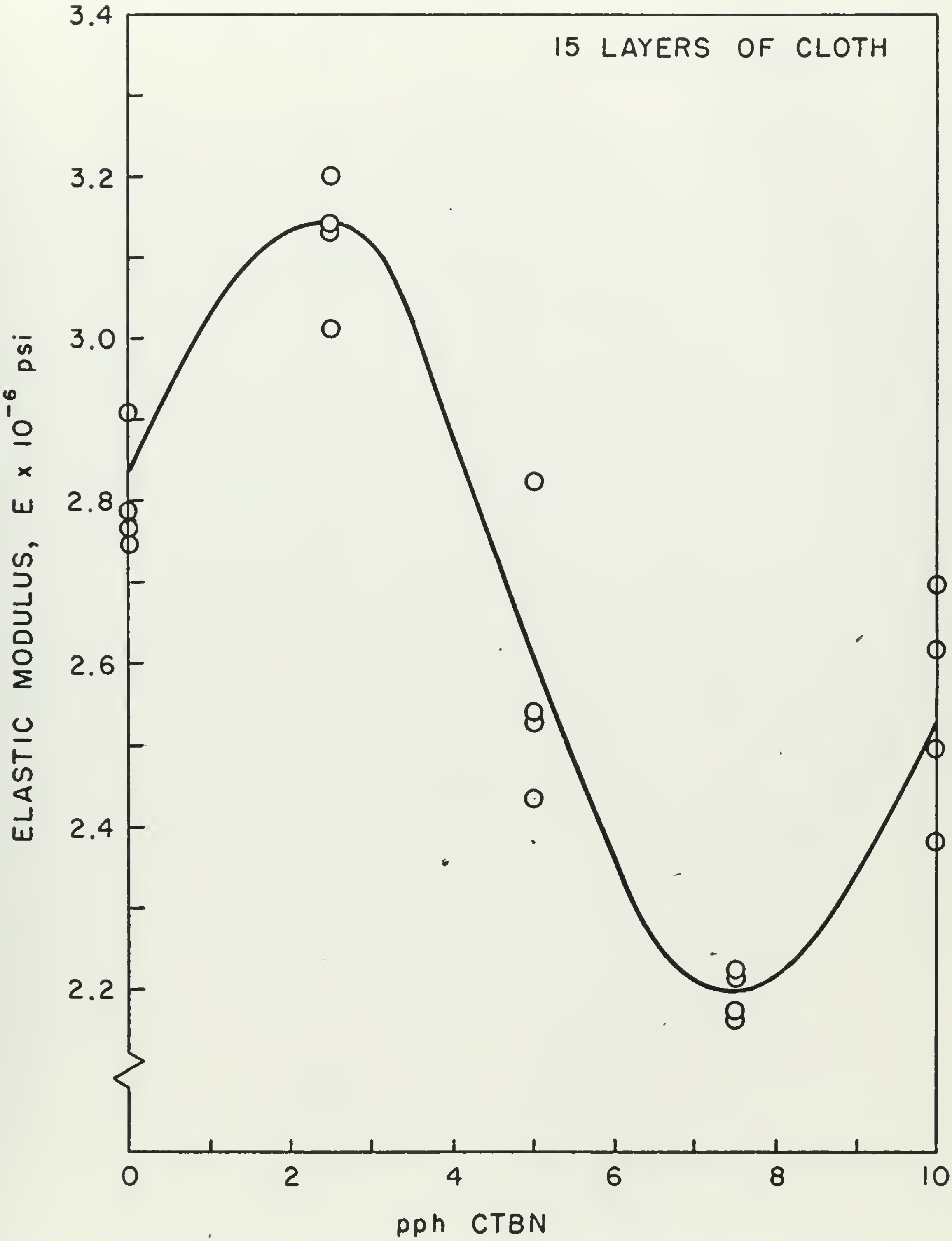


FIGURE 7. ELASTIC MODULUS vs. pph CTBN FOR 181 GLASS CLOTH LAMINATED WITH RUBBER MODIFIED POLYESTER RESIN.

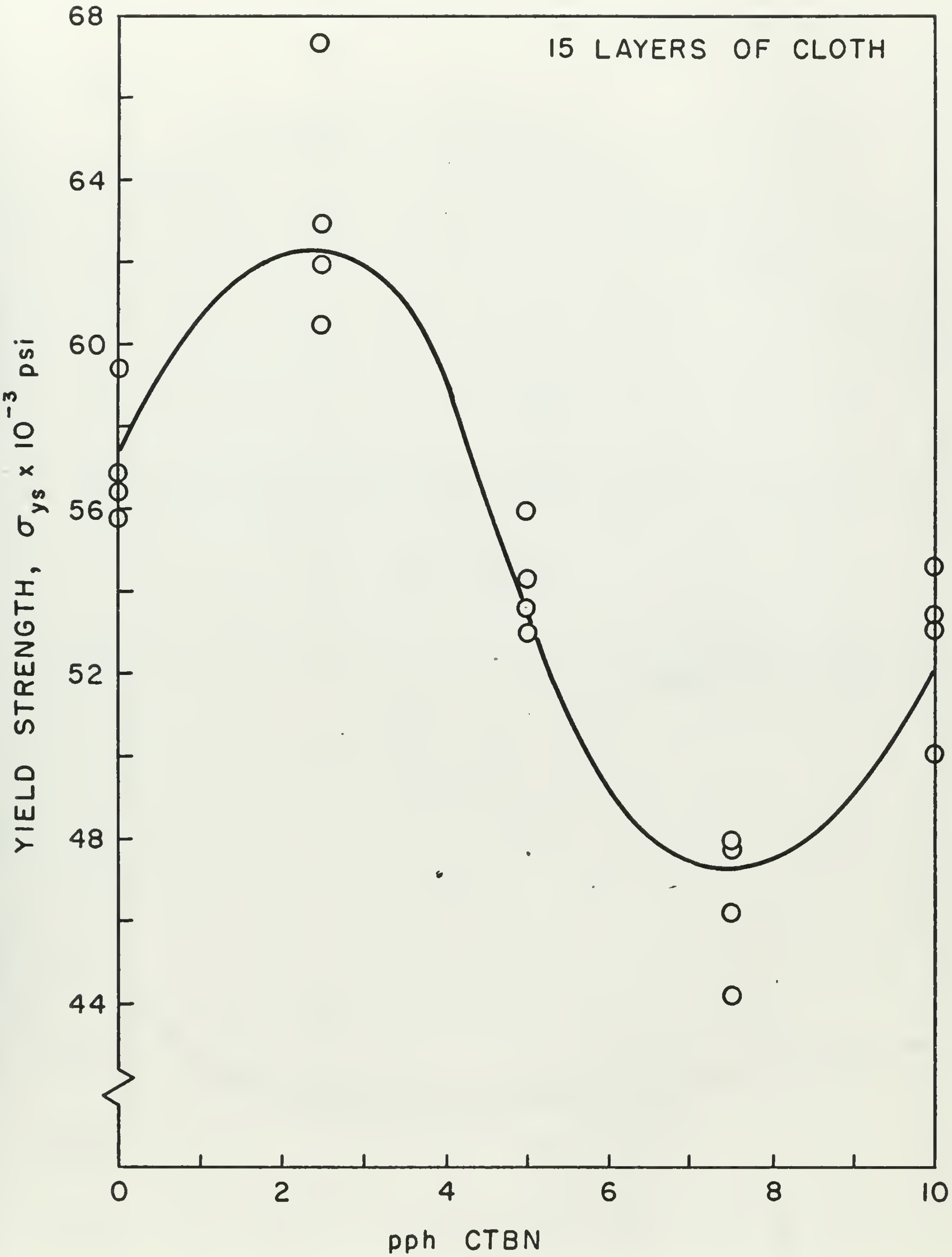


FIGURE 8. YIELD STRENGTH vs. pph CTBN FOR 181 GLASS CLOTH LAMINATED WITH RUBBER MODIFIED POLYESTER RESIN.

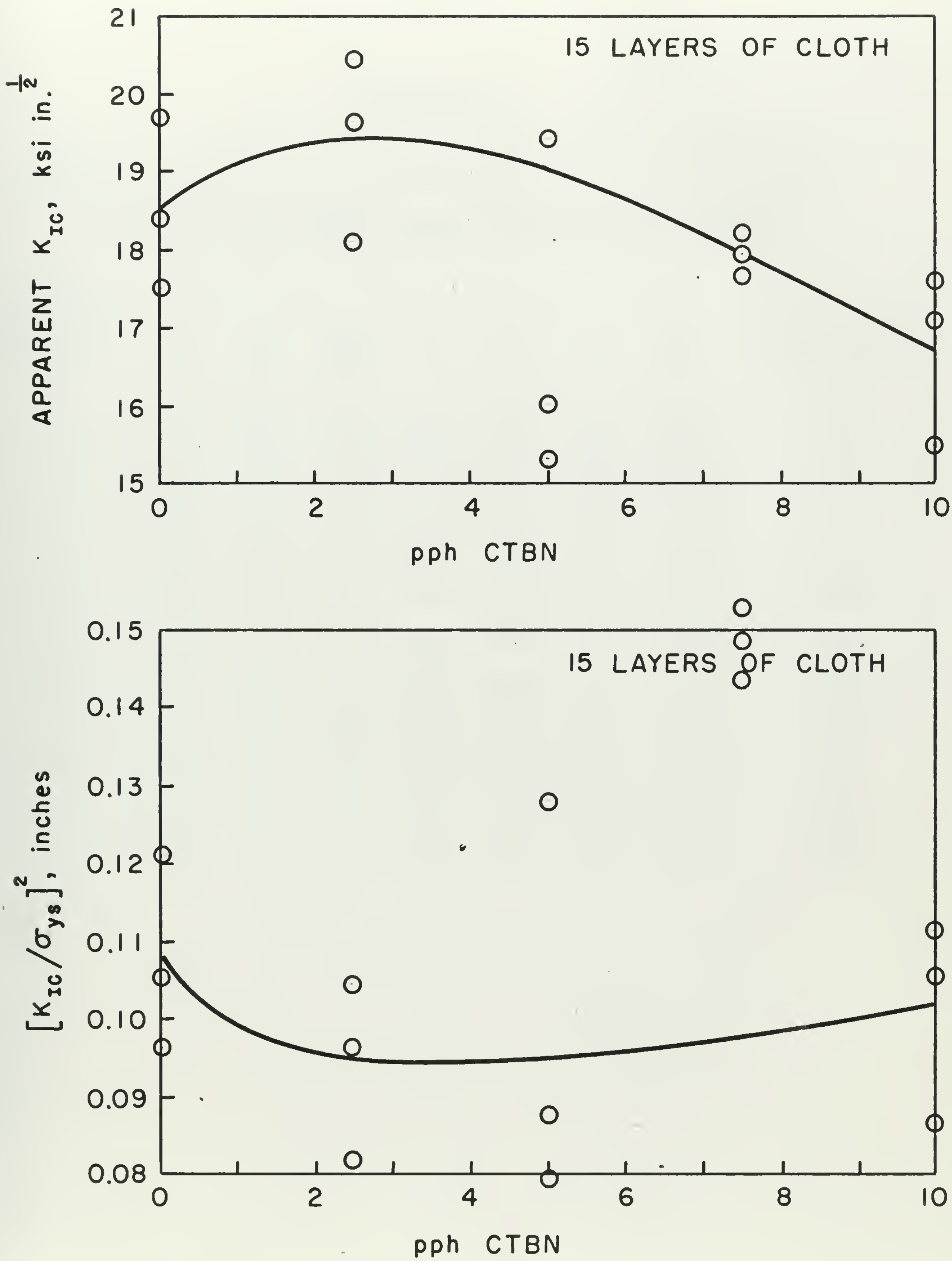


FIGURE 9. EFFECT OF CTBN ON APPARENT K_{IC} FOR 181 GLASS CLOTH LAMINATED WITH RUBBER MODIFIED POLYESTER RESIN.

TABLE 7

APPARENT K_{IC} CALCULATION OF RUBBER MODIFIED SPECIMENS

USING K CALIBRATION CURVE OF BROWN AND SRAWLEY

% Rubber Specimen Number	W	B	Web	P	a	Y	K_1	$[K_1/\sigma_{ys}]^2$
2.5-1	3.000	.115	1.080	3100	.960	2.23	19650	.0966
2.5-2	2.995	.126	1.320	3990	.838	2.12	20450	.1046
2.5-3	3.000	.136	1.372	3900	.814	2.10	18100	.0820
5.0-1	2.998	.138	1.304	3250	.847	2.12	15300	.0795
5.0-2	3.007	.125	1.300	3050	.854	2.13	16000	.0875
5.0-3	3.004	.114	1.340	3470	.832	2.11	19400	.1280
7.5-1	3.010	.137	1.340	3900	.835	2.11	18150	.1522
7.5-2	3.002	.135	1.370	3850	.816	2.10	17900	.1482
7.5-3	3.004	.126	1.325	3425	.840	2.12	17600	.1435
10.0-1	3.005	.134	1.408	3350	.799	2.09	15500	.0868
10.0-2	3.004	.127	1.380	3560	.812	2.09	17600	.1115
10.0-3	3.006	.117	1.342	3150	.832	2.11	17100	.1052

IV. DISCUSSION OF RESULTS

Thickness Effect

In the series of tests to determine thickness effect on apparent K_{IC} two analysis were carried out on each specimen. The reason for this was an initial discrepancy between values of K_{IC} determined using Bowie's formula and values obtained on four point bend specimens made from the same laminates. The curve fitting technique was then used and the results were comparable to those obtained in the four point bend specimens. A closer investigation showed that the discrepancy was due to the interpretation of σ as used in Bowie's formula. Originally it was interpreted to be the normal stress across the web (Force divided by area of rapid crack extension). The correct interpretation is the normal stress applied at infinity (Force divided by specimen cross-section, F/2bt). With this interpretation both methods gave comparable results.

The lower limit of thickness to obtain a valid K_{IC} measurement appears to be about .160 inches, or about 1.33 $[K_{IC}/\sigma_{ys}]^2$. This is substantially below the recommended 2.5 $[K_{IC}/\sigma_{ys}]^2$ value of Brown and Srawley (3). Requirements on specimen thickness B in terms of the plane stress plastic zone correction are also suggested. The plane stress plastic zone correction term, $r_y = \frac{1}{2\pi} [K_{IC}/\sigma_{ys}]^2$, should

be combined with specimen thickness, B, to give a value of $B/r_y > 4$. In this case we get a value of $B/r_y = 8.4$ above the recommended minimum value of 4.

Notch Depth

Notch depth had no apparent effect on K_{IC} in the range tested. The minimum notch depth tested was .25 inches. This is a value equal to 2.1 $[K_{IC}/\sigma_{ys}]^2$ again below the minimum recommended for brittle metals of 2.5 $[K_{IC}/\sigma_{ys}]^2$ For brittle metals K_{IC} does show an increase at smaller notch depths. This test was then tried with a thicker specimen, but failure at the pins resulted due to the increased force necessary for the smaller notch depths.

Strain Rate

Strain rate, as it does to other material properties, also affects the value of K_{IC} determined in the test. It appears that too slow or too fast strain rate will result in overestimating the true value of K_{IC}. It appears that between .1 and .5 inch per min. gives the true value of K_{IC}. There was difficulty encountered in this test at both extremes. At the lower strain rates, .01 and .02 inches/min., the crack would begin slow growth, increase in speed, run for about .125 inch, and then stop. The force would have dropped off and now begin to build again. This process would repeat itself until the crack was almost completely through the specimen. Measurement of the final unstable

crack growth and the force at which this occurred was therefore very difficult to perform accurately. At the higher strain rates it was difficult to observe the extent of stable crack growth using the staining technique. A strain rate of .05 inches/min. was chosen for the previous testing because at this rate stable crack growth could be monitored accurately and once crack growth went unstable, it went to failure.

<u>Strain Across Specimen</u>

The effect of varying the pin separation on the strain between the notches gave surprising results. The initial test had a 10 inch separation and then this was decreased at 2 inch increments down to 4 inches. The first three tests gave consistent results. Strain across the specimen was fairly constant. At four inch separation there was a deviation. It was felt that as the pin separation was decreased a point would be reached where the stress field would be greatest at the center of the specimen. Then, when crack growth started, it would run into an increasing stress field and rapid propagation would be aided by this increasing stress field. This is not substantiated by the test. In fact, the reverse seems to be true. At four inch pin separation the strain was greater at positions one and three and less in the center.

A reason for this might be that the assumption that the force is exerted from the center of the pin is incorrect. Looking at samples that had been tested showed stress whitening occurring at the extremeties of the diameter of the pin closest to the long diameter of the specimen. Two stress fields running parallel to the long dimension of the specimen were apparent. The stress whitening ran for 1 to 1 1/2 inches down from the pin on each side. Extending this down to the strain gages would put strain gages in positions one and three in line with this stress field. In effect, the specimen could be thought of as being pulled from two point sources, one inch apart, at each end. These specimens had not been reinforced with the aluminum plates as other specimens had.

The increment of strain as force was increased was constant. At about 2250 pounds stress relaxation started to become evident. While readings were being taken the force would drop off slowly and the strain indicator would show a decreasing strain.

<u>Rubber Modified Resin</u>

Elastic modulus and yield strength of the rubber modified resin composites appear to behave in a manner inconsistent with theory. Both increased at 2.5 percent rubber, dropped to be about equivalent to unmodified resin at 5.0 percent, decreased at 7.5 percent and increased to

be close to unmodified resin again at 10.0 percent. A search of literature showed that Sultan and McGarry (5) when plotting elastic modulus vs. pph CTBN showed a decreasing modulus. However, the scatter of their data indicates a possible variation similar to that obtained in this report.

The fracture toughness is improved slightly, 6 percent at 2.5 percent CTBN. It then decreases and beyond five percent seems to have a detrimental effect.

These variations, which are not consistent with current theory, could indicate different microscopic behavior as rubber content is varied. Perhaps the interactions of rubber particles, glass fibers, and resin change as the percentages of each are varied.

General Observations

The tensile specimens and the fracture toughness specimens appeared to fail in a completely different manner.

Tensile specimens displayed discoloring throughout the specimen. Upon fracture, there was large amounts of delamination, on some specimens running almost the entire length of specimen. The fracture surface appeared to be blown apart.

The fracture toughness specimens displayed a slow growth of stress whitening. Figure 10 (a) displays the type of stress concentration around a crack that is exhibited by

an isotropic homogeneous material in tension. The stress intensity occurs by a concentration of the stress fields as they bend around the notch. Figure 10 (b)-(f) display the growth of stress whitening displayed by the fracture toughness specimens in tension. The stress whitening starts as a small circle at the notch tip. As it grows it becomes distorted. The inner edge remains curved but the outer edge becomes parallel to the edge of the specimen. Eventually the fields join in the center. On fracture, the stress fields appear to be parallel to the edge of the specimen throughout.

At no time is there visual evidence of any stresses in the material between the notch tip and the edge of the specimen. Upon fracture there is only a small amount of delamination, indicated by crosshatched area of Figure 10 (f). It appears as if the material between the notch tip and edge of the specimen has a clamping effect on the remaining material preventing the large delaminations that occurred in the tensile specimens.

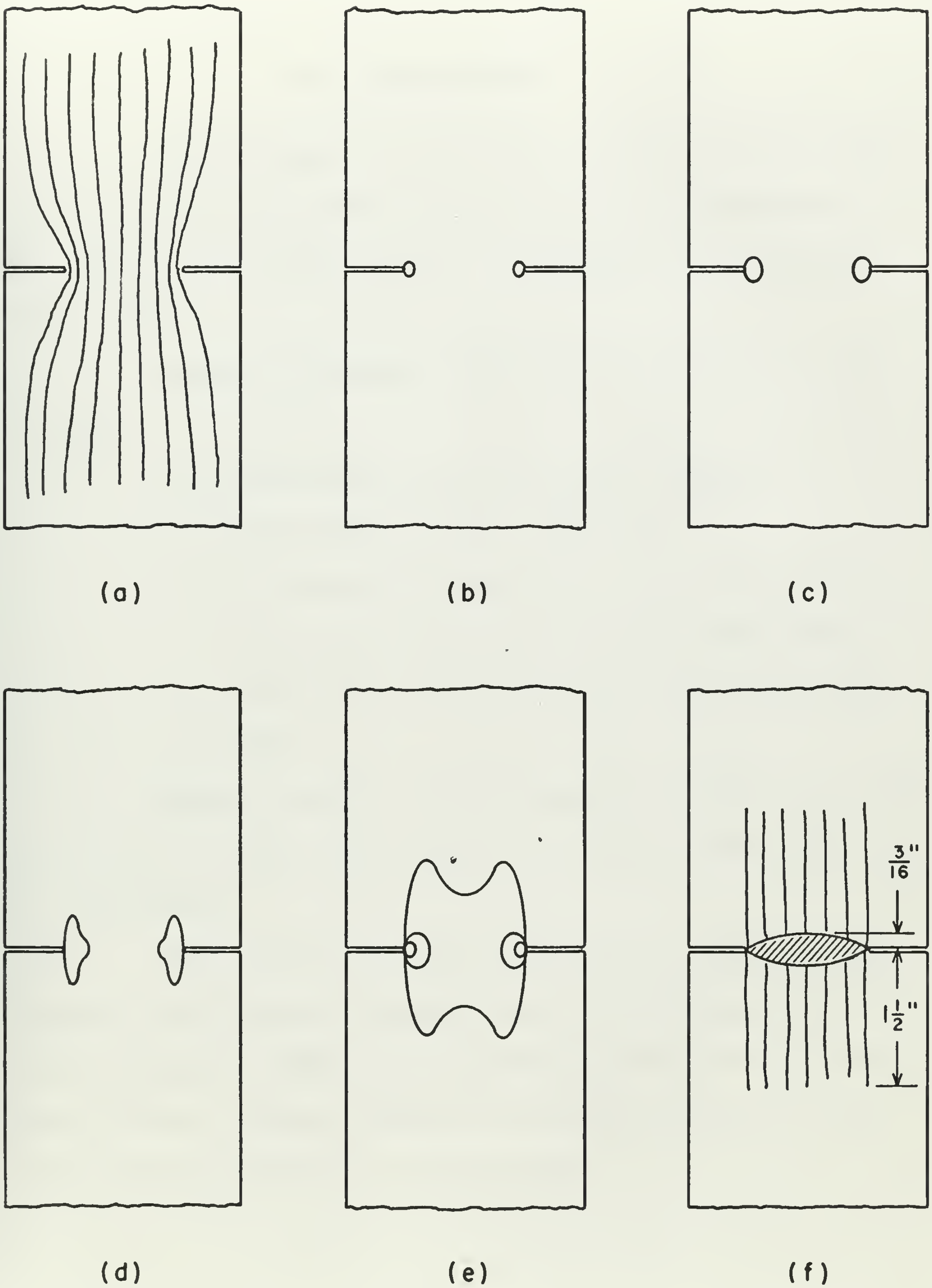


FIGURE 10. STRESS WHITENING.

V. CONCLUSIONS

On the basis of the work it appears to be valid to reduce the recommended minimum specimen dimensions of the ASTM (2) when applying the techniques to fiberglass composites.

Minimum dimensions that can be reduced are as follows:

1) Thickness reduced to 1.33 $[K_{1c}/\sigma_{ys}]^2$
2) Notch depth to 2.1 $[K_{1c}/\sigma_{ys}]^2$
3) Pin separation necessary for uniform strain across specimen can be reduced from three times specimen width to two times specimen width.

Minimum strain rate necessary for valid K_{IC} testing of double edge notched plates in tension was found to be .1 inch/min.

The addition of small amounts of CTBN was beneficial. The fracture toughness can be increased 6 percent with 2.5 percent CTBN. The addition of amounts of CTBN greater than 5 percent appears to be detrimental to the mechanical properties of the specimen.

VI. RECOMMENDATIONS

A great deal of additional data is necessary in order to reduce the degree of arbitrariness in setting the conditions for valid K_{IC} testing of fiberglass composites.

Tests of the type made for thickness effect should be made for notch depth, strain rate, glass content, specimen width and specimen length, using at least as many data points as used in the test for thickness effect. Tests of this type are very time consuming but no other satisfactory procedure is available.

The stress fields in the composite should be explored in greater depth. From the results of the strain gage readings and the visual observations of the stress whitening during testing it appears that theories applicable to isotropic, homogeneous materials will have little if any applicability to fiberglass reinforced plastics. It is suggested that samples be examined to determine whether failure results from poor bonding of the resin and glass, or actual breaking of the resin and glass as a single unit.

The effect of the fiberglass on arresting crack growth during the stable crack growth should also be investigated. With this mechanism fully understood, perhaps it could be expanded to improve the fracture toughness of the material.

It is recommended that further data be obtained on the effects of the addition of the CTBN to the composite. The spread of data would indicate that perhaps several different fracture mechanisms take place as the percentage of CTBN is increased.

VII. REFERENCES

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3. W. F. Brown, Jr. and J. E. Srawley, "Current Status of Plane Crack Toughness Testing," NASA TM X-52209, 1966.

4. O. L. Bowie, "Rectangluar Tensile Sheet with Symmetric Edge Cracks," Transactions, A.S.M.E. Journal of Applied Mechanics, 31, E, 2, June 1964, pp. 208-212.

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VIII APPENDIX

APPENDIX A

FABRICATION OF LAMINATES

The fiberglass reinforced plastic laminates that were tested were composed of Laminac Polyester Resin 4173 (American Cyanamid Company) reinforced by Style 181, a balanced weave, woven glass fabric (Stevens Fiberglass). Methyl ethyl ketone peroxide was used as the catalyst to insure proper cure. The laminates were layed up using a vacuum bag technique.

A vacuum bag was constructed from two pieces of mylar film. The mylar film was cut approximately one and a half inches bigger than the glass cloth on three sides and about four inches bigger on the fourth side. The bottom piece of mylar was lined around the edges with two thicknesses of mortite caulking compound. Small diameter rubber tubing was inserted along the inside edge of the caulking compound on the two sides that run perpendicular to the side with the four inch margin. Felt weather stripping was then placed along the inside edge of the tubing on the two sides with the tubing and on the inside edge of the caulking compound on the other two sides. Sufficient strips of weather stripping were used to fill the margin on all four sides.

The resin was mixed using an amount of Laminac 4173 equal to the weight of cloth utilized in the laminate.

Two percent by weight of methyl ethyl ketone peroxide was used as the catalyst and thoroughly mixed with the resin.

The bottom piece of mylar was coated with the resin mixture and three layers of cloth were inserted This procedure was repeated until the desired number of layers of cloth were used.

To control the thickness of laminates of equal number of layers of cloth, which in turn determines the percentage of glass in the laminate, steel spacers were used. These spacers were approximately one quarter inch by one inch by the desired thickness. The thickness desired could be determined by figuring that for approximately 70% of glass by weight in the finished laminate every three layers of cloth would take 1/32 of an inch thickness (i.e., 12 layer laminate, 1/8 inch thickness). These spacers were placed in the vacuum bag just outside the four corners of the cloth. The easiest procedure was to cut a piece out of the felt weather stripping adjacent to each corner of the cloth and place the spacers in this position.

The remaining piece of mylar was then placed over the bottom piece and pressed onto the caulking to insure an airtight seal. A vacuum pump nipple was inserted in the top piece of mylar near the edge corresponding to the side where the four inch margin was left. A vacuum pump was attached to the nipple and a suction taken to remove

the excess air. In order to remove air which has become entrapped in the resin and between the cloth layers, a spatula is used on the vacuum bag to force these bubbles (which are readily seen since upon complete wetting of the cloth, the laminate becomes transparent) into the felt lining. Once the bubbles are in the lining they migrate, under the action of the vacuum pump, to the nipple and are removed. The purpose of the rubber tubing was to aid this migration from the side furthest from the nipple and to help eliminate the air bubbles remaining in the felt from being squeezed back into the resin when the press makes contact with the felt. In the case of thin laminates, contact with the felt could occur before contact with the fiberglass and resin.

After all the air bubbles are removed, the vacuum bag arrangement is placed between two aluminum plates one half inch thick and placed in a hydraulic press. Pressure is increased until firm contact between the spacers, which were previously inserted, and the aluminum plates is assured. The laminate is held in the press under pressure for one hour at a temperature of 200°F. As soon as there is positive pressure on the laminate, the vacuum pump can be disconnected and the nipple removed. This prevents the nipple from becoming clogged and permits its reuse for additional laminates.

After one hour in the press the laminate is removed and placed in an oven at 250°F for two hours for post curing. It is then ready to be cut into specimens and tested.

Using this technique laminates of any size and thickness can be manufactured limited only by the maximum dimensions of the press available. Thickness can be varied by using different thickness spacers. It is important to insure that neither the felt weather stripping or the fiberglass cloth overhangs the spacers when the press makes contact. If this should occur it will change the glass content of the finished laminate.

APPENDIX B

SPECIMEN PREPARATION AND NUMBERING

The completed laminates were cut into both standard tensile specimens and fracture toughness specimens. The cutting of the laminates was done with a diamond edge saw. Tensile specimens were cut 3/4 inch by 10 inch and then shaped into the standard tensile specimen with a throat of one half inch. The fracture toughness specimens were cut three inches by eleven inches to conform as closely as possible to the overall dimensions of the double edge cracked plate specimens of reference 3.

The edge notches were then cut 5 1/2 inches from the end using a .025 inch saw. To conform to standards of reference 3 the notch depth was 3/4 inch for all testing, except when testing the notch depth effect on fracture toughness. A razor blade was then used at the root of each notch to reduce the root radius of the notch.

Reinforcement on the ends of each fracture toughness specimen was accomplished by applying a 3 inch by 3 inch piece of aluminum, .090 inch thick, to each side. This prevented fracture at the pins during testing. The aluminum was applied using an epoxy adhesive (Hysol Epoxi-Patch). Before applying the adhesive to the specimen and the aluminum plates, it was necessary to use a very coarse sandpaper on the surface of each. If the surface did not

feel rough to the touch, the adhesive would not bond properly and would shear off during testing. The epoxy requires 24 hours to cure after application.

The final step in the preparation of the specimen was to drill two one inch diameter holes. A series of carbide drills was necessary to accomplish this as it must cut through both the aluminum and the fiberglass. Three drills were used, 7/32 inch, 5/8 inch and 1 inch. The centers of the holes were placed 4 1/2 inches from the position of the notch, giving a 9 inch (three times the width) separation, center to center.

The specimens were numbered using a series of three numbers. The first number indicates the number laminate of a specific number of layers of cloth. The number of layers of cloth is indicated by the second number and the final number is the specimen number within that laminate.

For example: 2-18-3

2 - second laminate

18 - layers of cloth

3 - third specimen

For the rubber toughened matrix specimens the system used consisted of two numbers. All were fifteen layers thick so only the rubber percent and specimen number were needed. The first number indicated the rubber percent and the second the specimen number.

For example: 5.0 - 2

5.0 - 5% rubber

2 - second specimen

APPENDIX C

SAMPLE DATA

TABLE 8

TENSILE TESTS

Specimen Number	w	t	F	σ_{ys}	ΔP	ΔV	$E \times 10^{-6}$
3-6-1	.517	.054	1445	51,800	390	.006	2.33
3-6-2	.500	.049	1375	56,200	380	.006	2.58
1-6-1	.522	.060	1365	43,700	385	.006	2.05
1-6-2	.508	.057	1390	47,900	380	.006	2.18
1-6-3	.515	.050	1340	52,000	430	.006	2.77
1-6-4	.501	.059	1245	42,100	380	.006	2.14
2-6-1	.493	.045	1360	61,300	360	.006	2.70
2-6-2	.509	.045	1380	60,400	430	.006	3.12
2-6-3	.532	.047	1280	51,200	420	.006	2.80
2-6-4	.499	.044	1325	60,200	390	.006	2.95
1-9-1	.499	.073	2050	56,300	600	.006	2.75
1-9-2	.493	.073	1875	52,100	375	.004	2.60
1-9-3	.541	.069	2150	57,500	600	.006	2.68
2-9-1	.500	.074	2000	54,100	575	.006	2.59
2-9-2	.510	.073	2050	54,900	610	.006	2.73
2-9-3	.500	.072	1900	52,900	590	.006	2.73
2-9-4	.500	.071	1900	53,500	560	.006	2.62
2-9-5	.493	.070	1725	50,100	575	.006	2.77
1-12-1	.508	.111	2175	38,600	475	.004	2.14
1-12-2	.493	.109	2780	51,900	825	.006	2.56
1-12-3	.510	.104	2830	53,400	850	.006	2.67
1-12-4	.492	.108	2810	53,000	775	.006	2.44
1-12-5	.510	.111	2625	46,400	925	.006	2.72

Specimen Number	w	t	F	σ_{ys}	ΔP	Δv	$E \times 10^{-6}$
1-15-1	.497	.124	3480	56,500	1075	.006	2.91
1-15-2	.503	.123	3680	59,500	1020	.006	2.75
1-15-3	.483	.126	3400	55,900	1000	.006	2.74
1-15-4	.517	.121	3560	56.900	1050	.006	2.79
1-15-5	.500	.141	3260	46,300	1075	.006	2.55
2-15-1	.505	.121	3500	57,300	1025	.006	2.79
2-15-2	.487	.121	3400	57,600	1000	.006	2.82
2-15-3	.492	.123	3400	56.300	1060	.006	2.92
2-15-4	.510	.119	3360	55,500	1015	.006	2.79
2-15-5	.504	.126	3630	57,200	1035	.006	2.72
1-18-1	.506	.142	3950	54,900	1150	.006	2.66
1-18-2	.515	.143	4350	59,100	1425	.006	3.23
1-18-3	.501	.145	3925	54,000	1225	.006	2.81
1-18-4	.502	.146	4140	56,500	1250	.006	2.83
1-18-5	.507	.148	4300	57,300	1250	.006	2.78
2-18-1	.549	.154	4040	47,800	1150	.006	2.24
2-18-2	.507	.163	4030	48,800	1150	.006	2.32
2-18-3	.526	.163	4150	48,400	1260	.006	2.45
2-18-4	.519	.157	4410	53,200	1210	.006	2.48
2-18-5	.498	.169	4390	52,100	1150	.006	2.28
2-18-6	.502	.168	4460	52,800	1220	.006	2.41
1-24-1	.519	.171	3900	46,500	1300	.006	2.59
1-24-2	.506	.219	5920	53,300	1600	.006	2.40
1-24-3	.500	.215	5950	55,100	1600	.006	2.47
1-24-4	.511	.175	5300	59,300	1600	.006	2.98
1-24-5	.508	.219	5750	52,000	1600	.006	2.40

Specimen Number	w	t	F	σ_{ys}	ΔP	Δv	$E \times 10^{-6}$
2-24-1	.504	.207	5400	52,000	1550	.006	2.49
2-24-2	.501	.206	5150	50,000	1600	.006	2.59
2-24-3	.513	.203	6200	59,600	1050	.004	2.52
2-24-4	.505	.200	4700	46,500	1400	.006	2.31
2-24-5	.503	.210	4875	48,200	1400	.006	2.31
2-24-6	.503	.210	5775	57,200	1525	.006	2.51
1-30-1	.504	.225	7600	67,200	2500	.006	3.69
1-30-2	.504	.226	6150	54,000	2000	.006	2.92
1-30-3	.507	.237	6875	57,300	2050	.006	2.85
1-30-4	.508	.231	6800	58,100	1900	.006	2.71
1-30-5	.500	.231	6350	55,200	2000	.006	2.89
2-30-1	.496	.212	6000	57,200	1970	.006	3.12
2-30-2	.505	.216	6000	55,000	2000	.006	3.06
2-30-3	.502	.257	7250	56,200	2000	.006	2.58
2-30-4	.513	.260	6900	51,900	2000	.006	2.51
3-24-1	.480	.196	5700	60,700	1650	.006	2.93
3-24-2	.496	.195	5800	60,000	1700	.006	2.74

TABLE 9

APPARENT K_{1c} CALCULATION USING BOWIE ANALYSIS

Specimen Number	2l	t	Web	F	σ	a	K_1	$[K_1/\sigma_{ys}]^2$
2-30-1	3.025	.216	1.405	6240	9540	.810	18270	.110
2-30-2	3.004	.227	1.362	7030	10300	.821	20000	.132
2-30-3	3.040	.242	1.285	7280	9900	.878	20300	.136
2-24-1	3.036	.200	1.478	5820	9590	.779	17850	.124
2-24-2	2.997	.200	1.303	5390	9000	.847	18000	.126
2-24-3	3.040	.203	1.280	5280	8550	.880	17600	.120
2-18-1	3.025	.164	1.313	4500	9070	.856	18200	.130
2-18-2	3.043	.171	1.425	4750	9140	.809	17500	.120
2-18-3	3.040	.167	1.352	4620	9100	.844	18100	.129
2-15-1	3.043	.121	1.390	3820	10350	.827	20200	.127
2-15-2	3.045	.122	1.378	3570	9600	.834	18800	.110
2-15-3	3.040	.117	1.151	2950	8300	.945	18150	.102
1-12-1	3.045	.103	1.384	3200	10200	.831	19900	.167
1-12-2	2.992	.100	1.382	3150	10520	.805	20200	.172
1-12-3	3.039	.106	1.152	2620	8140	.944	17800	.134
2-9-1	3.038	.070	1.327	2250	10600	.856	21300	.161
2-9-2	3.045	.071	1.225	1975	9130	.910	19200	.131
2-9-3	3.046	.071	1.255	2050	9520	.896	19850	.140
1-6-1	3.040	.056	1.288	1440	8470	.876	17350	.140
1-6-2	3.035	.052	1.379	1540	9760	.828	19050	.168
1-6-3	3.016	.047	1.372	1420	10000	.822	19400	.175

TABLE 10

APPARENT K_{1c} CALCULATION USING K CALIBRATION

CURVE OF BROWN AND SRAWLEY

Specimen Number	W	B	Web	P	a	Y	K_1	$[K_1/\sigma_{ys}]^2$
2-30-1	3.025	.216	1.405	6240	.810	2.80	17850	.105
2-30-2	3.004	.227	1.362	7030	.821	2.10	20000	.132
2-30-3	3.040	.242	1.285	7280	.878	2.14	19800	.129
2-24-1	3.036	.200	1.478	5820	.779	2.07	17480	.119
2-24-2	2.997	.200	1.303	5390	.847	2.12	17520	.120
2-24-3	3.040	.203	1.280	5280	.880	2.14	17200	.115
2-18-1	3.025	.164	1.313	4500	.856	2.12	17800	.124
2-18-2	3.043	.171	1.425	4750	.809	2.09	17200	.116
2-18-3	3.040	.167	1.352	4620	.844	2.11	17650	.122
2-15-1	3.043	.121	1.390	3820	.827	2.09	19750	.121
2-15-2	3.045	.122	1.378	3570	.834	2.10	18400	.105
2-15-3	3.040	.117	1.151	2950	.945	2.18	17500	.096
1-12-1	3.045	.103	1.384	3200	.831	2.10	19500	.160
1-12-2	2.992	.100	1.382	3150	.805	2.095	19700	.163
1-12-3	3.039	.106	1.152	2620	.944	2.15	17000	.122
2-9-1	3.038	.070	1.327	2250	.856	2.12	20800	.154
2-9-2	3.045	.071	1.225	1975	.910	2.16	18880	.126
2-9-3	3.046	.071	1.255	2050	.896	2.15	19280	.132
1-6-1	3.040	.056	1.288	1440	.876	2.14	16920	.133
1-6-2	3.035	.052	1.375	1540	.828	2.10	18600	.161
1-6-3	3.016	.047	1.372	1420	.822	2.10	19050	.169

TABLE 11

STRAIN FIELD

SPECIMEN 1-18-2 10 INCH PIN SEPARATION

Force	MR No. 1	Inc.	Total Strain	MR No. 2	Inc.	Total Strain	MR No. 3	Inc.	Total Strain
0	9554	--	--	11290	--		12090	--	--
250	9709	155	155	11450	160	160	12268	178	178
500	9852	143	298	11592	142	302	12430	162	340
750	9980	128	426	11730	138	440	12580	150	490
1000	10110	130	556	11860	130	570	12720	140	630
1250	10268	158	714	12010	150	720	12890	170	800
1500	10380	112	826	12140	130	850	13015	125	925
1750	10518	138	964	12270	130	980	13155	140	1065
2000	10670	152	1116	12410	140	1120	13310	155	1220
2250	10800	130	1246	12522	112	1232	13425	115	1335
2500	10940	140	1386	12648	126	1358	13560	135	1470
2750	11100	160	1546	12780	132	1546	12780	130	1600
3000	11200	120	1666	12895	115	1605	13790	100	1700

TABLE 12

STRAIN FIELD

SPECIMEN 1-18-3 8 INCH PIN SEPARTION

Force	MR No. 1	Inc.	Total Strain	MR No. 2	Inc.	Total Strain	MR No. 3	Inc.	Total Strain
0	10270	--	--	11780	--	--	118950	--	--
250	10430	160	160	11930	150	150	12045	150	150
500	10565	135	295	12079	140	290	12185	140	290
750	10710	145	440	12208	138	428	12330	145	435
1000	10855	145	585	12340	132	560	12470	140	575
1250	10995	140	725	12480	140	700	12615	145	720
1500	11140	145	870	12615	135	835	12760	145	865
1750	11290	150	1020	12745	130	965	12895	135	1000
2000	11430	140	1160	12880	135	1100	13035	140	1140
2250	11565	135	1295	13010	130	1230	13155	120	1260
2500	11705.	140	1435	13135	125	1355	13290	135	1395
2750	11850	145	1580	13265	130	1485	13425	135	1530
3000	12000	150	1730	13390	125	1610	13525	100	1630

TABLE 13

STRAIN FIELD

SPECIMEN 1-18-1 6 INCH PIN SEPARATION

Force	MR No. 1	Inc.	Total Strain	MR No. 2	Inc.	Total Strain	MR No. 3	Inc.	Total Strain
0	11635	--	--	12060	--	--	11695	--	--
250	11820	185	185	12243	183	183	11870	175	175
500	11970	150	335	12360	117	300	11985	115	290
750	12100	130	465	12480	120	420	12118	133	423
1000	12230	130	595	12600	120	540	12230	112	535
1250	12380	150	745	12730	130	670	12350	120	655
1500	12510	130	875	12850	120	790	12460	110	765
1750	12670	160	1035	12970	120	910	12600	140	905
2000	12800	130	1165	13100	130	1040	12720	120	1025
2250	12960	160	1325	13250	150	1190	12860	140	1165
2500	13115	155	1480	13380	130	1320	12990	130	1295
2750	13240	125	1605	13520	140	1460	13140	150	1445
3000	13400	160	1765	13640	120	1580	13250	110	1555

TABLE 14

STRAIN FIELD

SPECIMEN 2-18-3 4 INCH PIN SEPARATION

Force	MR No. 1	Inc.	Total Strain	MR No. 2	Inc.	Total Strain	MR No. 3	Inc.	Total Strain
0	11392	--	--	12032	--	--	10850	--	--
250	11560	168	168	12140	108	108	10980	130	--
500	11760	200	368	12240	100	208	11135	155	285
750	11960	200	568	12350	110	318	11285	150	435
1000	12160	200	768	12460	110	428	11435	150	585
1250	12360	200	968	12575	115	543	11590	155	740
1500	12565	205	1173	12690	115	658	11750	160	900
1750	12780	215	1388	12810	120	778	11920	170	1070
2000	12990	210	1598	12920	110	888	12090	170	1240
2250	13245	255	1853	13060	140	1028	12270	180	1420
2500	13465	220	2073	13175	115	1143	12440	170	1590
2750	13730	265	2338	13312	137	1280	12640	200	1790
3000	13965	235	2573	13435	123	1403	12830	190	1980